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The GPS flight experiment on TOPEX/POSEIDON

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Abstract. The precision orbit determination (POD) experiment on TOPEX/POSEIDON using the Global Positioning System (GPS) is yielding concrete results. Orbit consistency and accuracy tests indicate that GPS is routinely providing satellite altitude with an accuracy of better than 3 cm. Here we review the GPS experiment, its basic concepts, POD techniques and key results, and discuss the possible cost and performance benefits that may flow to future missions.

Introduction

TOPEX/POSEIDON was launched on 10 August 1992 through the joint efforts of the National Aeronautics and Space Administration (NASA) and the Centre National d'Etudes Spatiales (CNES). Its mission is to study ocean circulation by measurement of sea surface topography. During the following 3-5 years, it will map regional and global ocean currents and their time variation by observing their surface signatures with two precise (2-3 cm) microwave altimeters. In the 1970s and 80s, the Geosat and Seasat missions returned valuable information about mesoscale oceanic features and variability but more in-depth study was limited by large orbit uncertainties in the geocentric radial position of the altimeter. For example, using the Doppler and satellite laser ranging (SLR) systems that were available then, the best Seasat orbits obtained from POD have a radial accuracy of about 40 cm root-mean-square (RMS). Although that can suffice for regional and ocean variability studies, global circulation requires decimeter radial accuracy or better. Therefore, the TOPEX/POSEIDON Project substantially raised its planned orbit altitude to 1336 km to reduce drag and gravity perturbations, and selected two operational precise tracking instruments—a laser reflector array and a Doppler receiver to track the signals from the French network of radio beacons known as DORIS [Nouel *et al.*, 1988]. It also supported development of the ground segments of those systems, and of improved spacecraft dynamic models. The Project also developed a GPS flight receiver as an experiment and supported the implementation of a global GPS tracking network and a ground data processing system.

This overview, along with three papers [*Yunck et al., Schutz et al., Christensen et al.*, 1994] discuss different aspects of the GPS experiment, including early POD results. Here we review the basic GPS system concepts, summarize recent results, and consider their implications for future missions.

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GPS Tracking System Elements

The GPS tracking system consists of: the GPS constellation, the TOPEX/POSEIDON GPS receiver, a global network of GPS ground reference receivers, and a central monitor, control and processing facility. The POD strategy requires continuous tracking of the GPS satellites that are concurrently observable by the ground and flight receivers. Data from all receivers are brought together and processed in a global solution in which the TOPEX/POSEIDON orbit, all GPS orbits, receiver and transmitter clock offsets, and other parameters are estimated. Simultaneous sampling at all receivers (which may be achieved by later temporal interpolation) eliminates the effect of common errors, such as clock errors in the satellites and receivers.

The Global Positioning System

Each of the 24 satellites in the GPS constellation broadcasts two navigation signals to the Earth's surface, or in the space below about 3000 km altitude. The two L-band carrier frequencies, 1.57542 GHz (L1) and 1.2276 GHz (L2), are coherently derived from a fundamental oscillator at 10.23 MHz through multipliers of 154 and 120, respectively. Each L-band carrier is modulated with a precise pseudorandom ranging code, known as the P-code, that enables the receiver to determine precisely and unambiguously the arrival time of each code bit and to recover the phase of the carrier. The L1 signal is also modulated in quadrature by a less precise ranging code known as the C/A-code. Dual-frequency observations permit nearly perfect correction of the ionospheric delay. Typically 5 to 9 GPS satellites are observable within a hemispherical field of view.

GPS is equipped with two distinct security mechanisms known as selective availability (SA) and anti-spoofing (AS). SA denies the highest real-time GPS absolute position and velocity accuracies to unauthorized users by dithering the 10.23 MHz clock frequency. AS prevents the mimicking of GPS signals ("spoofing") by hostile forces by encrypting the P-code on the L1 and L2 carriers, while leaving the C/A code on L1 unaltered. By using GPS in a differential mode, clock errors cancel and SA has no effect on performance. The TOPEX/POSEIDON receiver has no decryption capability because it was considered experimental; consequently, it can track only the L1 carrier phase using the C/A code when AS is on. Without L2, ionospheric delays above TOPEX/ POSEIDON cannot be measured which can result in decimeter-level orbit error. NASA had an inter-agency agreement with the Department of Defense during 1993 for guaranteed periods of AS-free operations. This agreement must be renegotiated for the future.

The GPS Flight System

The Monarch™ GPS flight receiver, which was built by Motorola Inc. under contract to the Jet Propulsion Laboratory

(JPL), tracks up to 6 GPS satellites concurrently and reports the measurements of carrier phase at a rate of 1 sample/sec and the P-code range, which are averaged, at 1 sample/10 sec. Phase measurement errors are better than 4 mm. Phase center variation of the antenna with elevation and azimuth angles was measured prior to launch and is known to better than 5 mm. The GPS antenna is atop a 4.3 m mast to avoid reflected signals (*i.e.*, multipath) from the spacecraft. With the total mass of the Earth accurately known, the reference radial position of the phase center relative to the spacecraft center of gravity (cg) is solved for in the POD. Its daily repeatability over the past year is ≤5 mm RMS; the position of the actual cg probably varies this much in time because of on-orbit changes in the spacecraft configuration.

The GPS Global Tracking Network

Only about a dozen globally distributed ground sites are needed to obtain full accuracy because the satellite's orbital motion provides ample flight/ground covisibility of the GPS satellites. The locations of these sites are known in the International Terrestrial Reference Frame (ITRF) [Boucher and Altamimi, 1992] to an accuracy of about 2 cm from space geodetic observations spanning a decade. These sites are part of the global network operated by the International GPS Service and sponsored by the International Association of Geodesy; the Service provides very accurate tracking and POD products for geodynamics programs.

The GPS Operations Center

All transactions involving GPS data and POD products flow through the operations center, which automatically retrieves data from all GPS sources—about 8 Mbyte/day from the flight receiver and 1 Mbyte/day from each ground site. The center monitors and controls the ground and flight receivers and initiates actions to repair system faults. The ground receivers can store data up to 12 days to protect against communication outages. In the first 6 months of experimental operation we acquired 99% of the possible data from the flight receiver when GPS AS was turned off, and approximately 95% from the ground receivers. Data acquisition and editing, POD production and validation are semi-automated. An analyst checks the results for accuracy and completeness and decides whether reprocessing is needed. Precise orbits from GPS are now produced with 30-hour data arcs on 24-hour centers, providing 6-hr overlaps for orbit comparisons. These orbits and statistical quality measures are available about 3 hrs after all data for 1 day are received. External release of the orbits occurs about 1 week after each 10-day orbit repeat cycle. The end-to-end GPS POD system – flight and ground operations, POD, and data archival and access functions – requires a total work force of five persons.

POD Strategies

Traditional POD techniques, which depend on precise models of satellite forces to recover the orbit, were expected in the 1980s to be limited on TOPEX/POSEIDON to approximately 13 cm by force model errors. A group at JPL turned to geometrical techniques, which are less sensitive to dynamical limitations, and soon realized that the enveloping coverage given by GPS offered an almost ideal solution. By the mid-1980s, a strategy known as reduced dynamic tracking emerged that sought to combine the best elements of dynamical and geometrical positioning to minimize overall error [Wu *et al.*, 1991]. The extraordinary tracking coverage provided by GPS, the continuity of high-accuracy tracking data in three dimensions, and the wide GPS satellite covisibility from the flight and ground receivers provide a geometric data strength unrivaled by any other system. SLR, for example, provides highly accurate slant-range measurements during short intervals (10-15 min), but large coverage gaps along the orbit remain. This observational weakness must be overcome with precise models of all forces acting on the spacecraft. DORIS with its 40-50 station ground network provides more coverage but uses an inherently weaker range rate measurement. The continuous 3-D position change vector provided by GPS gives the analyst new options for reducing POD errors arising from deficiencies in the spacecraft dynamic models and in the measurements.

Full Dynamic POD

In a fully dynamic approach the orbital motion of the spacecraft is strongly constrained by dynamic models. Deficiencies in those models, if unaccounted for, can result in magnified POD errors in components of the state vector that are weakly observed because the least squares process will channel the model errors into those components. SLR and DORIS are restricted to a nearly full dynamic POD strategy because of their incomplete tracking coverage and/or limited observability. A least squares adjustment of empirical (e.g., once-per-revolution) force parameters to account for the model errors is used with these tracking systems to significantly reduce orbit error. Although this achieves some of the benefit of a reduced dynamic strategy, more frequent relaxation tends to significantly increase POD error for these ground-based tracking systems. A purely geometric solution would be essentially singular.

Reduced Dynamic POD

With GPS data one can approach a purely geometric solution, and lessen the influence of force model errors, by adding to the dynamic model a 3-dimensional stochastic acceleration vector that is re-estimated (subject to *a priori* constraints) at each time step (e.g., every 5 min). This purely local adjustment will rely more on geometry and measurement accuracy rather than on dynamics. Each component of the acceleration vector is characterized as a first-order Markov process constrained by an assigned correlation interval and a variance on its white noise driver. These stochastic series are introduced into the TOPEX/POSEIDON dynamic model and adjusted after a converged full dynamic POD solution is obtained to further reduce the residuals. (For the higher altitude GPS satellites a nearly full dynamic POD approach is retained.)

Reduced dynamic POD attempts to optimize the result by choosing the constraints (variance and correlation time of the stochastic vector) to balance dynamic error against geometric limitations – to draw the best from both the models and the measurements. Dynamic model errors still appear but at a diminished level that depends on the stochastic constraints. The optimal values of the constraints will depend on the relative geometric/dynamic strength. Ultimately, the best GPS-based orbit solutions will come from a dual approach [Yunck *et al.*, 1993; Schutz *et al.*, 1993] that strives to improve the dynamic models and the measurement system.

For TOPEX/POSEIDON a purely geometric solution (i.e., lifting all constraints from the stochastic force estimate) leads to degraded accuracy. The Monarch™ can track only six satellites at once, and the current onboard satellite selection algorithm (which can be modified) holds the effective field of view to less than a hemisphere, limiting geometric strength. Radial accuracy falls to 12-15 cm with a nearly geometric solution. Covariance studies indicate, however, that a full sky all-in-view receiver could provide geometric POD accuracies of ~2 cm [Wu *et al.*, 1991].

Summary of the Analyses

Two groups (JPL and the Center for Space Research (CSR) at the University of Texas) have been analyzing the TOPEX/POSEIDON GPS data. In addition, Goddard Space Flight Center (GSFC), CSR and CNES use SLR/DORIS data to generate precise orbits and to improve the dynamic models. CSR has focused on a near full dynamic POD strategy, steadily refining the force models using GPS and SLR/DORIS data; JPL has pursued reduced dynamic POD. An almost stunning convergence of the two approaches has resulted.

A battery of quantitative measures of performance have been developed. These include internal data quality and orbit consistency tests (post-fit residuals, formal errors, orbit overlap agreements); direct comparisons of GPS solutions between groups and with SLR/DORIS solutions; and objective external tests, such as altimeter crossover residuals. Each approach has limitations, but each provides a necessary condition toward assessment of accuracy.

The improved force models derived by GSFC and CSR [Nerem *et al.*, in preparation, Marshall *et al.*, 1993] from the TOPEX/POSEIDON SLR/DORIS tracking include a tuned "box-and-wing" spacecraft macromodel for drag and radiation effects, and several gravity models.

It is telling that, without exception, when a refined dynamic model has been introduced, the agreement between the re-computed dynamic orbit and the GPS reduced dynamic orbit has improved. Early GSFC and CSR SLR/DORIS orbit solutions employing the prelaunch gravity (JGM-1) and macro-models differed in altitude from the reduced dynamic GPS solutions by ~6 cm RMS with pronounced geographical correlations [Christensen *et al.*, 1993]. GSFC's tuned macro-model brought this down to about 5 cm. A new JGM-2 model, tuned with TOPEX/POSEIDON SLR and DORIS data, reduced this to about 3.5 cm. A later gravity model, JGM-3, improved by adding TOPEX/POSEIDON GPS data [Tapley *et al.*, in preparation], has brought the RMS altitude agreement between SLR/DORIS dynamic solutions and GPS reduced dynamic solutions to around 2.5 cm.

While the dynamic and reduced dynamic agreement is close, we note that so long as significant dynamic model errors (drag, gravity, thermal, solar) remain, a well-tuned reduced dynamic solution should in theory do better. TOPEX/ POSEIDON altimeter crossover residuals [Christensen *et al.*, 1993; Yunck *et al.*, 1993] which are dominated by ocean variability, are slightly but consistently lower using the GPS reduced dynamic solutions. For a global distribution over 36,000 crossover points collected during Feb-May 1993 the variance of the crossover residuals for the GPS reduced dynamic orbits is about 10 cm^2 lower than that obtained from the Project orbits generated by GSFC and CNES using SLR and DORIS tracking [*Bertiger et al.*, in preparation]. One can infer from this result that the geographically uncorrelated component of the radial orbit error is greater than $\sqrt{5}$ cm RMS for the SLR/DORIS orbits; $\sqrt{5}$ cm would apply only if the GPS orbits were perfect. If the GPS orbit accuracy is in fact 3 cm, then the SLR/DORIS orbit accuracy is near 4 cm.

The reduced dynamic technique has itself been refined during the mission, as illustrated by the agreement on overlaps of consecutive 30-hr solutions [Yunck *et al.*, 1993]. Early solutions agreed in altitude to about 5 cm RMS in the overlap region. Tuning of the stochastic force constraints, refinement of the GPS satellite orbit solutions, use of better gravity models, and other strategy tweaks have brought this to about 1 cm, with some full 10-day cycles (9 overlaps) averaging 6-7 mm.

Discussion and Conclusions

A number of improvements in GPS POD are still possible. GPS satellite orbit errors tend to dominate the TOPEX/POSEIDON error budget. Our solutions are about a factor of two better [Bertiger *et al.*, 1993] when all of the GPS satellites are non-eclipsing, which occurs 12% of the time. Mismodeled GPS satellite dynamics are more troublesome during eclipse periods. We will improve the GPS satellite maneuver and phase center models, adopt site- and elevation-dependent data weighting, extend the GPS satellite solution arcs, add empirical force adjustments to the GPS satellite orbit solutions, and improve the dynamic models for the GPS satellites.

One clear message from these results is that both the dynamic and reduced dynamic techniques are surpassingly accurate on TOPEX/POSEIDON because of its high altitude and extensive modeling. But future missions at lower altitudes will face a tougher challenge. Below 700 km, atmospheric drag and gravity-induced errors grow dramatically for full-dynamic POD solutions. TOPSAT, a proposed NASA mission for very high accuracy land topography measurements using interferometric altimetry, proposes to fly at 560 km yet requires 7 cm RMS altitude accuracy; it cannot consider use of ground-based tracking systems alone. Reduced dynamic tracking can, in principle, sustain few-centimeter accuracy down to the lowest altitudes. Figure 1 shows the projected POD accuracies for ground-based and GPS tracking as a function of altitude, assuming in the latter case a 12-channel GPS receiver and full sky field of view. (At 800 km a full field of view will see 13-17 GPS satellites continuously.) This figure is based on error analyses that consider the effect of mismodeled observational and dynamic errors, including drag. This figure predicts that attaining sub-5 cm radial accuracy at altitudes below 1000 km will be elusive for drag-limited spacecraft (no accelerometers onboard) using SLR and/or DORIS.

The GPS experiment has demonstrated that the production of operational precise orbits from the GPS POD system has a number of distinct advantages: fewer ground stations, extensive automation in data handling, use of expert systems and fewer people. These factors will keep the recurring costs of the GPS POD system and the marginal cost to support an additional mission exceptionally low. The GPS flight receiver procurement cost today would be less than 1% of the actual cost of the TOPEX/POSEIDON spacecraft.

AS can be accommodated on future missions without loss of POD accuracy with a receiver that uses either a codeless technique or a decryption capability to recover L2 carrier phase. GPS POD accuracy on TOPEX/POSEIDON is far from being limited by phase noise. Although the L1 carrier phase measurement accuracy of the Monarch receiver is about 4 mm @ 1 sec, we select only 1 sample every 5 min for POD on TOPEX/POSEIDON. Improved digital signal processing in

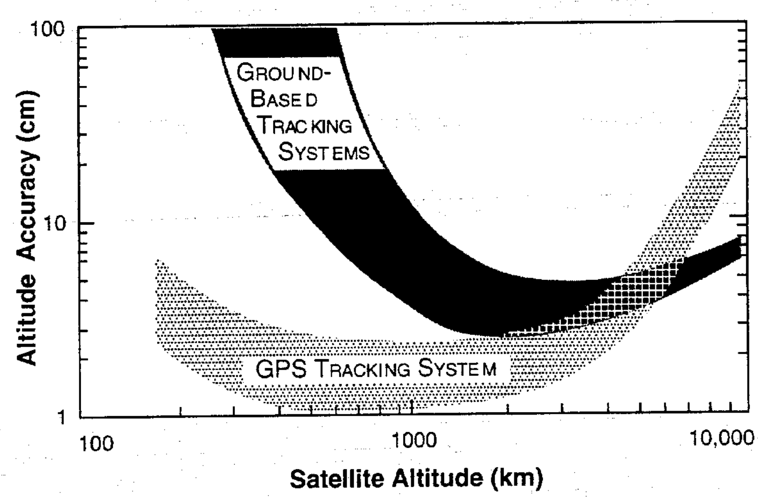

Figure 1. Estimated POD accuracy for drag-limited satellites. Upper bound for ground systems applies for sparsely tracked spacecraft with poor dynamic modelling. Upper bound for GPS system applies to the case of restricted GPS observational geometry such as provided by TOPEX/POSEIDON. Lower bound applies to the "all-in-view" geometry.

future receivers could achieve better than 0.2 mm @ 1 sec using decryption and 2 mm using a codeless technique.

While the GPS advantage for missions like TOPSAT is evident, full implications go deeper. GPS enables a new class of low-cost and low-orbit altimetry missions. Centimeter tracking at lower altitudes allows the use of low-power, solid-state, dual-band, altimeters. For a given precision, the required altimeter radiated power varies as the fourth power of altitude. Lower power enables smaller solar arrays on smaller satellites that are launched by smaller launch vehicles. Altimetry missions like TOPEX/POSEIDON follow-on can be significantly cheaper because of GPS.

With NASA and its international partners now planning a series of ocean altimetry missions into the next century, the lessons of the TOPEX/POSEIDON GPS experiment could not be more timely.

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